Flow through the Straits of the Philippine Archipelago Simulated by Global HYCOM and EAS NCOM

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LONG-TERM GOALS

We are collaborating with other DRI participants to better evaluate and understand the dynamics seen in observations and model results within the Philippine Archipelago, a strategic region with numerous straits. The model results come from the .08° and .04° global HYbrid Coordinate Ocean Model (HYCOM) and .088° East Asian Seas (EAS) Navy Coastal Ocean Model (NCOM) nested in global NCOM, the .04° global HYCOM and some finer nests starting in FY09, the others from the outset.

OBJECTIVES

Objectives of our DRI participation are (1) high resolution simulations (with and without tides; with and without data assimilation) that provide a larger scale context for the observations, (2) model-data comparisons with the measurements, (3) studies of observational representativeness in measuring transports through straits, (4) investigation of non-tidal and tidal (barotropic and internal) influences on specific sub-regions of interest, especially where measurements are available, and (5) to provide boundary conditions for nested models.

APPROACH

Ocean models: HYCOM: Traditional ocean models use a single coordinate type to represent the vertical, but no single approach is optimal for the global ocean. Isopycnal (density tracking) layers are best in the deep stratified ocean, pressure levels (nearly fixed depths) provide high vertical resolution in the mixed layer, and σ-levels (terrain-following) are often the best choice in coastal regions. The generalized vertical coordinate in HYCOM allows a combination of all three types (and others), and it dynamically chooses the optimal distribution at every time step via the layered continuity equation. NCOM uses σ-levels when the depth is shallower than 137 m and z-levels, optionally with partial cell topography, elsewhere.

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Both models use a C-grid, have scalable, portable computer codes that run efficiently on available DoD High Performance Computing (HPC) platforms, and have a data assimilation capability. EAS NCOM runs with tides and tides have been added as an option in global HYCOM.

Task (1) (corresponding to the list in the objectives) High resolution ocean model simulations: Run HYCOM globally with .08° (9 km equatorial) and .04° (4 km equatorial) resolution, the latter starting in FY09. These are run largely under the sponsorship of partnering and related projects (see Related Projects below). Run simulations with high frequency climatological forcing and run interannually at least over the time frame of the International Nusantara STratification ANd Transport (INSTANT) and DRI data sets. Run simulations with and without tides, and with and without data assimilation.

The .088° EAS NCOM (17°S-52°N, 98°E-158°E) has been running in real-time with tides and data assimilation since October 2003. It receives boundary conditions from .176° (20 km) equatorial resolution global NCOM (with data assimilation but no tides).

Nested models of the Philippine Seas using HYCOM and NCOM are also planned. Both models already have a robust nesting capability. During the first 3 years the nests would have 3 km resolution and during years 4-5 a Philippine Seas nest in .04° global HYCOM would have 1.5 km resolution. The nested models will be very useful (1) for investigating the impact of resolution on other aspects of the simulations, (2) as boundary conditions for even higher resolution nested models of Philippine Seas subregions run by other DRI participants, and (3) for data representativeness studies. Even same resolution nests will be useful in studying the impacts of tides, different vertical mixing schemes and parameter choices, and data assimilation on other aspects of the Philippine Seas circulation.

Task (2) Model-data comparison studies: Model-data comparisons are used to evaluate and improve the models and to help interpret the data. Data that resolve tidal frequencies and measure straits transports, the vertical structure of the water column, and the nature of its variability are particularly useful. Measures of year-long means and seasonal variability are also valuable. Model output will be archived at measurement locations with sufficient temporal resolution for tides. Measurements used in conjunction with models are vital in studying the roles that tides and other processes play in determining transports though straits and the vertical structure of the water column. Timely access to DRI data will greatly facilitate this process and opportunities for joint publications with other DRI participants are highly desirable, particularly in years 3-5.

Task (3) Studies of data representativeness: All of the models listed in Task (1) can be very useful in assessing the ability of DRI observational arrays to measure integral properties, such as straits transport (both in terms of spatial coverage and length of record), particularly if they perform well in the model-data comparisons (Task 2). They can also be used in estimating appropriate corrections in data analyses. Doing this using a suite of model simulations, rather than just one, and picking models that best match the data should improve the quality of corrections and enhance confidence in the results.

Task (4) Study the interaction of tidal and non-tidal processes in subregions of DRI interest: The Philippine Seas form a region where large amplitude external and internal tides may have a significant impact on the non-tidal circulation and water mass structure. We are particularly interested in collaborative studies and joint publications on related topics with other DRI participants in subregions of DRI interest.

Task (5) Provide boundary conditions for nested models of other DRI participants: Output from global HYCOM and NCOM are used for this purpose. The boundary conditions can have resolution as fine as 3 km during years 1-3 and as fine as 1 km during years 4-5. Advance coordination is needed to make sure the required time period is archived at the temporal resolution and locations needed. We are also interested in model inter-comparisons to investigate the impact of model resolution and design on the simulation of processes in the vicinity of straits.

WORK COMPLETED

Output from data-assimilative real-time runs of .08° global HYCOM and .088° EAS NCOM was provided to aid mission planning for the 2nd PhilEx Intensive Observational Period (IOP) (March 2009) cruises. Results from non-assimilative climatologically-forced and assimilative interannually-forced simulations of the Philippine Seas were forwarded to the observational team with emphasis on straits where intensive sampling was planned. These included cross-sections of the temperature, salinity and velocity as well as time series of transport through the inflow and outflow straits. Output from both real-time systems was posted on the NRL web pages for guidance.

The first .04º global HYCOM simulations (4.4 km resolution in the Philippines) were run a total of 8.7 model years in collaboration with other projects, starting on 12 January 2009. This is the highest resolution ever for a global ocean model with high vertical resolution (2x finer horizontal grid spacing). It was run at NAVOCEANO using an HPC Challenge grant of computer time from the DoD HPC Modernization Program. Strait sill depths in the Philippine Archipelago were modified to improve accuracy, but much more work is needed. For comparison, near twin .08º global HYCOM simulations were also integrated, including the same climatological 6-hourly atmospheric forcing (derived from the European Centre for Medium-Range Weather Forecasts 40-year reanalysis, ERA-40, with wind speed scaled using a monthly climatology from the QuikScat scatterometer; Kara et al., 2009) and bottom topography derived from the same .04º data set. However, the .08º topography was subjected to numerous hand edits in past years, mainly in shallow water and particularly to straits and sill depths, while the .04º global topography has received relatively few edits, mainly in FY09 to the Philippine and Indonesian Archipelagos.

Results and model-data comparisons from .04º and .08º global HYCOM and .088º EAS NCOM were presented at the August 2009 PhilEx DRI meeting at the University of Hawaii. The Wiki server was a useful source of DRI data.

Boundary conditions from the real-time data assimilative .08° global HYCOM system were extracted and provided to the Rutgers group running the Regional Ocean Modeling System (ROMS). These included hindcasts five days in arrears, the nowcast and then up to a four day forecast when available. Unfortunately, supercomputer issues during the two winter 2009 cruises often prevented the entire daily hindcast through forecast cycle from being integrated to completion and this limited our ability to provide boundary conditions. In addition, atmospheric forcing (wind stress, heat fluxes and precipitation) from the 0.5° NOGAPS was provided. These were the same fields used to force global HYCOM.

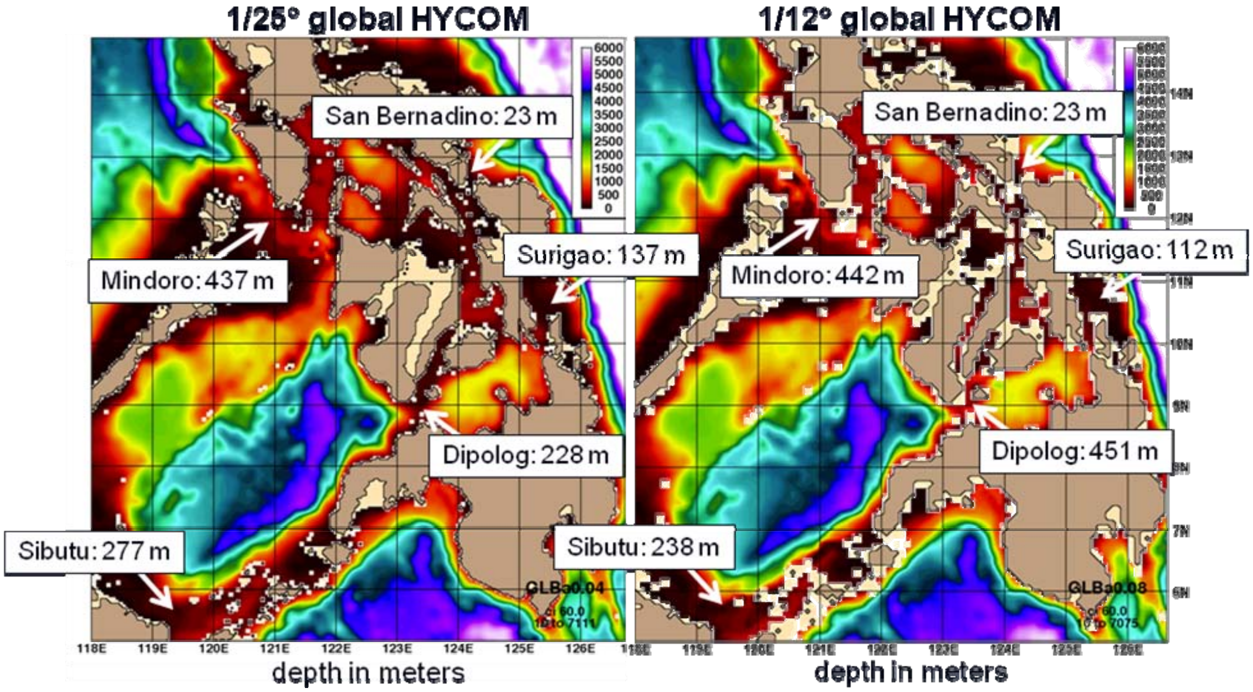

Figure 1: Bottom topography (in meters) of the seas in and around the Philippine Islands used in .04° global HYCOM (left) and .08° global HYCOM (right). The color bar for depth in meters is located in the upper right corner of each panel. The sill depths (i.e. the shallowest depth along the deepest channel through the strait) at the key inflow/outflow passages are noted.

RESULTS

Figure 1 demonstrates the close agreement between the .04º and .08º global HYCOM topographies in deep water. Most of the sill depths are in good agreement, with the largest differences being the Dipolog Strait sill depth and the Sibutu Passage topography and sill depth. The mean straits transports and mean currents at 20 m depth, shown in Figure 2, depict a very large increase in transport through Mindoro Strait from .08º to .04º global HYCOM (where the topography and sills depths are in good agreement) and Sibutu Passage, but a relatively modest increase through Surigao and Dipolog (despite the very large sill depth error in Dipolog in .04º global HYCOM). These results indicate that the mean transport through the former is largely determined by the outflow through Sibutu Passage, while the latter is mainly determined by the inflow through Surigao. Thus, it is most critical to improve the topography and sill depths of Sibutu Passage and the adjacent passages along the ridge. There is also a 2.6x increase in transport through the very shallow San Bernardino Strait, despite no difference in sill depth. Thus, other factors such as different topography, increased numerical accuracy at higher resolution, and reduced horizontal friction because some friction parameters scale with resolution also have an impact on flow through the straits. The increased transport through San Bernardino has a marked impact on the mean flow through the interior passages of the Philippines between the Surigao and Mindoro Straits. In .08º (.04º) global HYCOM there is a net transport of .12 Sv (.04 Sv) from Surigao to Mindoro versus .14 Sv (.36 Sv) from San Bernardino to Mindoro.

Figure 3 depicts vertical cross-sections of mean meridional velocity from .04º and .08º global HYCOM across the latitude of a DRI mooring in the southern Mindoro Strait. The annual mean and the means

of two contrasting seasons are shown. The mooring location (red vertical line) captures the deepest flow very well in the .04º model (less well in the .08º model). At shallower depths it captures the vertical structure of the mean flow and its seasonal variations, but not its strength. The strongest flow lies to the west, interrupted by a shallow bank in the channel that lies just to the north of (directly in) the cross-section from the .04º (.08º) model. Further, because this mooring is located in an area of strong horizontal gradients in the model currents, it is difficult to use it in assessing the currents and transports simulated by the models, except in the deepest part of the channel. A similar problem exists in Dipolog Strait, where a shallow bank lies just upstream of the mooring location.

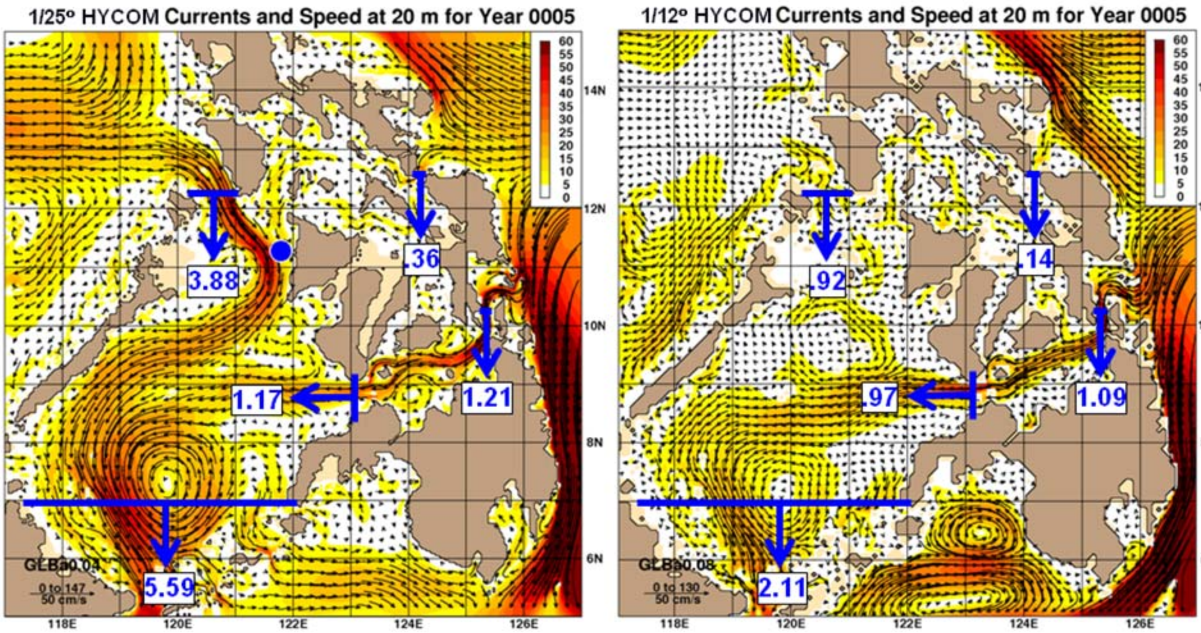

Figure 2: Mean currents (cm/s) overlain on speed (colors) at 20 m depth in and around the Philippine Seas from .04° global HYCOM (left) and .08° global HYCOM (right). The mean is based on model year five. The blue arrows and values indicate the direction and magnitude (respectively) of the full water column transport at the key inflow/outflow passages defined in Figure 1. The blue dot in the southern Mindoro Strait indicates the location of the Panay mooring. The speed contour interval is 5.0 cm/s and the reference vector (50 cm/s) is in the lower left corner.

Figure 4 is a comparison between the nearly 2-year observed mean (June 2007 - March 2009) meridional velocity component at the mooring location shown in Figure 3, year 5 means from .04º and .08º global HYCOM with climatological atmospheric forcing and no data assimilation, and the mean from real-time EAS NCOM with tides and data assimilation over the mooring time period. In our FY08 PhilEx DRI ONR report (Hurlburt and Metzger, 2009), we included comparisons between the June-December 2007 observed mean zonal velocity component at the same mooring location with two earlier .08º global HYCOM simulations, one with and one without tides. In that case only the simulation with tides showed the observed bottom-trapped current, but in those simulations the topography was too shallow by > 200 m, a problem corrected in the HYCOM simulations shown in Figure 4, but not corrected in EAS NCOM. However, both of the FY09 HYCOM simulations (without tides) simulate the observed bottom-trapped current, with stronger and more realistic speeds in .04º

global HYCOM. EAS NCOM with tides and the shallow depth bias does not depict the observed bottom-trapped current, but unlike HYCOM it depicts the the reversal to northward mean flow in a surface layer.

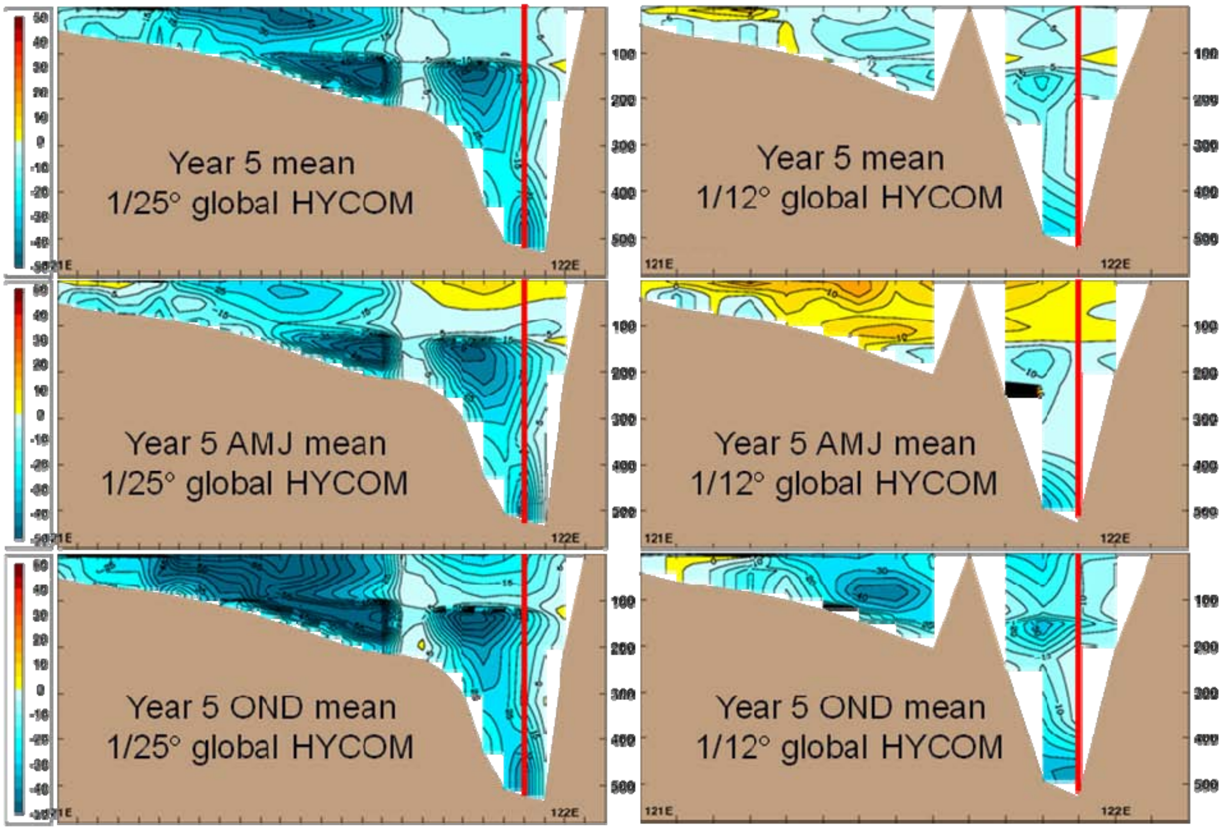

Figure 3: Cross-section at 11.29°N of mean meridional velocity (cm/s) from the surface to 500 m depth at the latitude of the Panay mooring (depicted by the blue dot in Figure 2 and noted as the red line in these panels). The cross-section extends zonally from 121°E to the coast of Panay Island. The left column is from .04° global HYCOM and the right column from .08° global HYCOM. The top row is the year five mean, the middle row is the year five April-May-June mean and the bottom row is the year five October-November-December mean. Yellow-orange colors indicate northward flow and blue colors indicate southward flow. The contour interval is 5 cm/s.

In our FY08 PhilEx report (Hurlburt and Metzger, 2009), we also showed that .08º global HYCOM only simulated the persistent observed cyclonic gyre in the Bohol Sea when tides were included in the model. However, .04º global HYCOM also simulates it without tides (Figure 5). In this figure every velocity vector is plotted and the improved ability of the model to depict complex mean flows in this region is clearly illustrated. In addition, global HYCOM simulates the 4-layer flow through Dipolog Strait observed by the PhilEx mooring (marked by a blue dot on Figure 5; results not shown). This four-layer flow is simulated more strongly in .04º global HYCOM, which has a large sill-depth error in Dipolog (Figure 1).

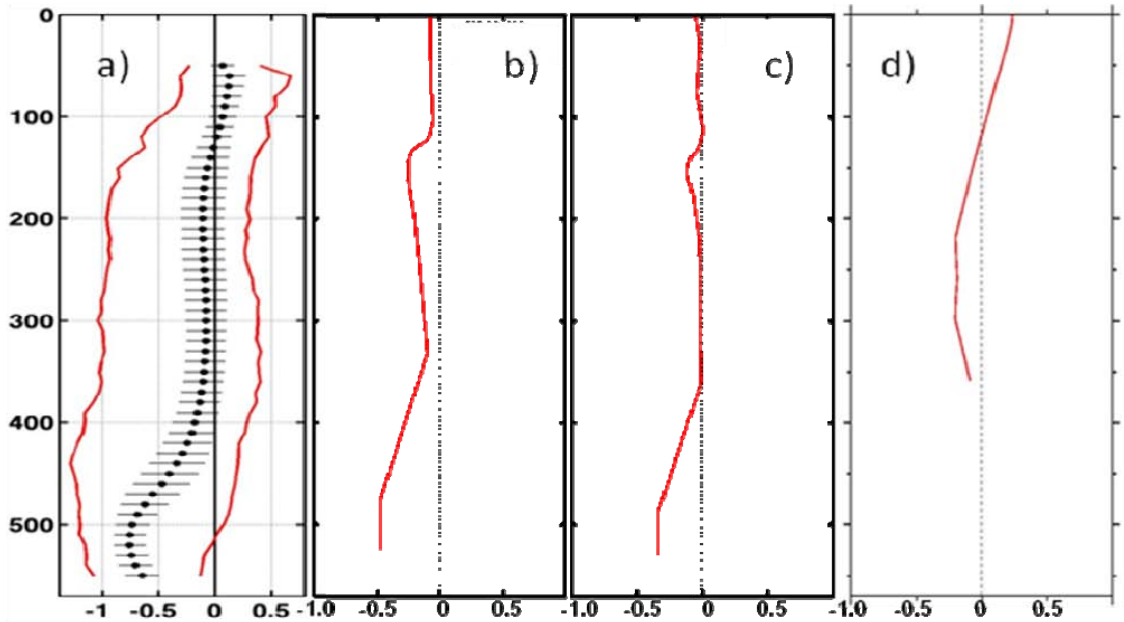

Figure 4: Mean meridional velocity (m/s) profiles in the southern Mindoro Strait at the Panay mooring site from the a) ADCP over the approximate time frame June 2007 through March 2009, b) 0.04° global HYCOM for model year five, c) 0.08° global HYCOM for model year five, and d) 0.088° EAS NCOM over the same time as the observations. The red lines in panel a) are ±1 standard deviation.

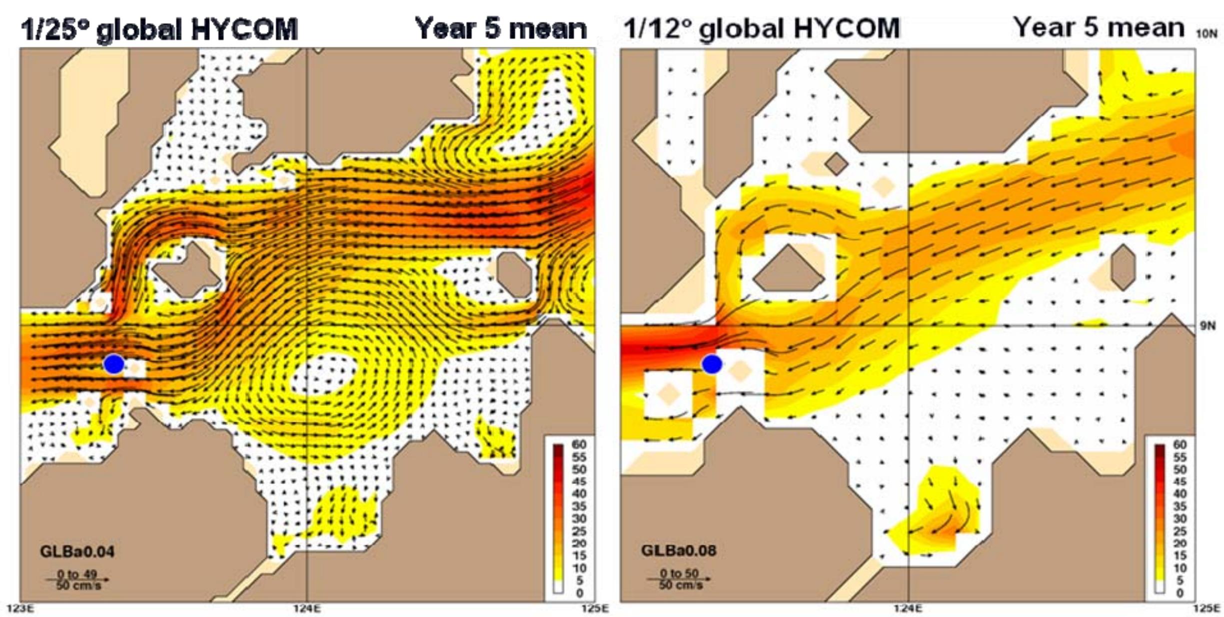

Figure 5: Mean currents (cm/s) overlain on speed (colors) at 20 m depth in the Bohol Sea in .04° global HYCOM (left) and .08° global HYCOM (right). The mean is based on model year five and every model vector is plotted. The blue dot indicates the location of the Dipolog Strait mooring. The speed contour interval is 5.0 cm/s and the reference vector (50 cm/s) is in the lower left corner.

In our FY08 PhilEx report (Hurlburt and Metzger, 2009), we included a snapshot of internal tides simulated by .08º global HYCOM in the Philippine Archipelago and a model-data comparison in the western Sulu Sea. As a follow-up we note that the HYCOM snapshot depicted internal tidal generation at four of the five locations observed by imagery within the Philippine Seas (Sibutu Passage and by far the strongest generator, Mindoro Strait, Surigao Strait, and Dipolog Strait, but not San Bernardino Strait). The observed generation locations are from a presentation at the August 2009 PhilEx DRI meeting by C. Jackson and A. Gordon.

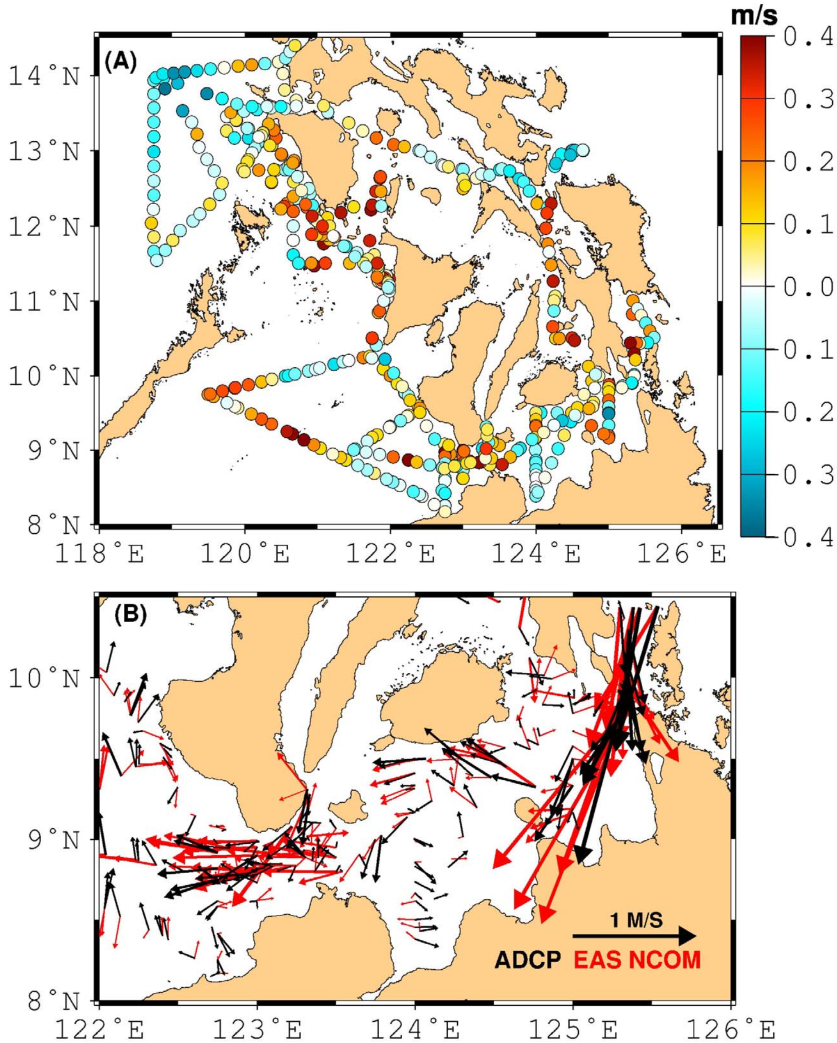

Figure 6: ADCP depth averaged (25-55 m) velocities (m/s) from the January 2008 PhilEx cruise versus EAS NCOM depth averaged velocities at the nearest hour with respect to the data. (A) Speed differences (EAS NCOM minus ADCP) along the ship track and (B) velocity vectors from ADCP data (black) and EAS NCOM (red) for a zoom on the Bohol Sea region and the reference vector (1 m/s) is in the lower right corner. Model-data verification statistics for the entire region are a vector correlation of 0.56, a root mean square (rms) speed difference of 0.27 m/s, data mean speed ± standard deviation of 0.25±0.19 m/s, and model mean speed ± standard deviation of 0.33±0.31 m/s.

Figure 6 depicts a comparison between instantaneous EAS NCOM and hull-mounted ADCP speeds (6a) and velocities (6b) (both averaged over 25-55 m depth) from the January, 2008 PhilEx cruise. Since EAS NCOM includes tides and the tides can make a significant contribution to the instantaneous currents, the model and data velocities were compared at the nearest hour. The strong currents through Surigao Strait and, to a lesser extent, Dipolog Strait are also seen in EAS NCOM, but EAS NCOM fails to represent the cyclonic gyre in the Bohol Sea shown in the ADCP vectors. Over the entire region, the vector correlation between EAS NCOM and ADCP velocities is 0.56. In addition, the EAS NCOM mean speed and especially speed variability are biased high.

IMPACT/APPLICATIONS

The .04° (3.5 km mid-latitude) resolution, first used in some FY09 global HYCOM simulations, is the highest so far for a global ocean model with high vertical resolution. As demonstrated in this report, the resolution increase from .08° to .04° in global HYCOM has a major impact on our ability to simulate the circulation in a complex archipelago with interior seas, numerous small islands, and narrow straits within a global ocean model. However, improved knowledge of the topography and sill depths of the Philippine Archipelago is essential because hydraulic control makes the flow through the straits very sensitive to the accuracy of the straits topography and sill depths. A global ocean prediction system, based on .04° global HYCOM with tides, is planned for real-time operation starting in 2012. At this resolution, a global ocean prediction system can directly provide boundary conditions to nested relocatable models with ~1 km resolution anywhere in the world, a goal for operational ocean prediction at NAVOCEANO.

In the ONR PhilEx DRI, output from .04° and .08° global HYCOM and .088° EAS NCOM are providing the larger scale context of the circulation in the Philippine Seas and real-time nowcast and forecast output from data-assimilative .08° global HYCOM is being used as boundary conditions for a real-time regional ROMS system run by the group at Rutgers University.

TRANSITIONS

Global NCOM is operational at NAVOCEANO while .088° EAS NCOM and .08° global HYCOM are running in real time. Global HYCOM was transitioned to NAVOCEANO at the end of FY08 and operational testing is planned in FY10. It is receiving 6.4 SPAWAR funding (see below) for evaluation/validation. NAVOCEANO made the decision not to make EAS NCOM an operational product, but the system will continue to run in real-time for the duration of this DRI.

RELATED PROJECTS

As partnering funding, we support related Indonesian/Philippines Seas work using two existing 6.1 NRL Base projects: “Global remote littoral forcing via deep water pathways” (H. Hurlburt, PI) and “Dynamics of the Indonesian throughflow (ITF) and its remote impact” (E.J. Metzger, PI). Related projects supporting global HYCOM also substantially benefit this DRI project. These include the multi-institutional effort to develop a next generation eddy-resolving global ocean prediction system using HYCOM. This effort was supported by the FY04-08 NOPP project, “U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model (HYCOM)” (http://www.hycom.org) (H. Hurlburt, NRL PI), which ended on 31 Dec 2008, and a related 6.4 project, “Large Scale Prediction”

(E.J. Metzger, PI). The computational effort is strongly supported by DoD HPC Challenge and non-challenge grants of computer time. In FY09 .04° and .08° global HYCOM ran under a new FY09-11 DoD HPC Challenge grant.

REFERENCES

Hurlburt, H.E. and E.J. Metzger, 2009. Flow through the straits of the Philippine Archipelago simulated by global HYCOM and EAS NCOM. *Ocean Battlespace Sensing*, Office of Naval Research Annual Report FY2008. (published on CD-ROM; available on-line at http://www7320.nrlssc.navy.mil/pubs.php)

Kara, A.B., A.J. Wallcraft, P.J. Martin, and R.L. Pauley, 2009. Optimizing surface winds using QuikSCAT measurements in the Mediterranean Sea during 2000–2006, J. Mar. Syst., doi:10.1016/j.jmarsys.2009.01.020.